NEGATIVE ABSOLUTE TEMPERATURE

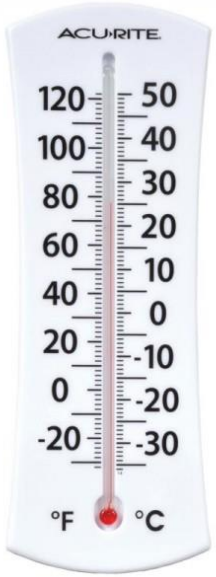
By Isaac Woodard

Outline

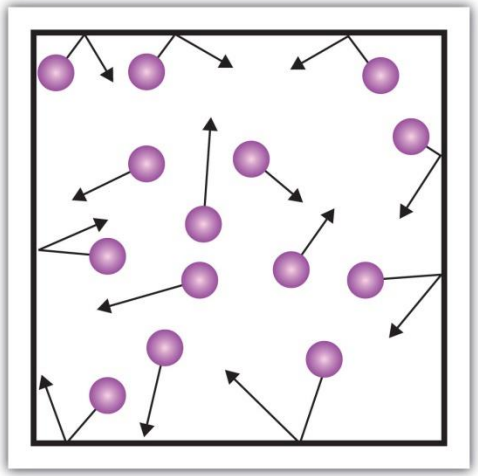
1. Temperature & Entropy
2. Negative Temperature
3. The Two-State Paramagnet
4. Lasers & Population Inversions
5. Summary & Implications

What is Temperature?

- Something measured with a thermometer
- Average kinetic energy of particles



https://www.acurite.com/8-thermometer-00322.html



http://www.rock-cafe.info/suggest/liquids-particles-movement-6c697175696473.html

Multiplicity

https://imgur.com/gallery/PQq1Xod

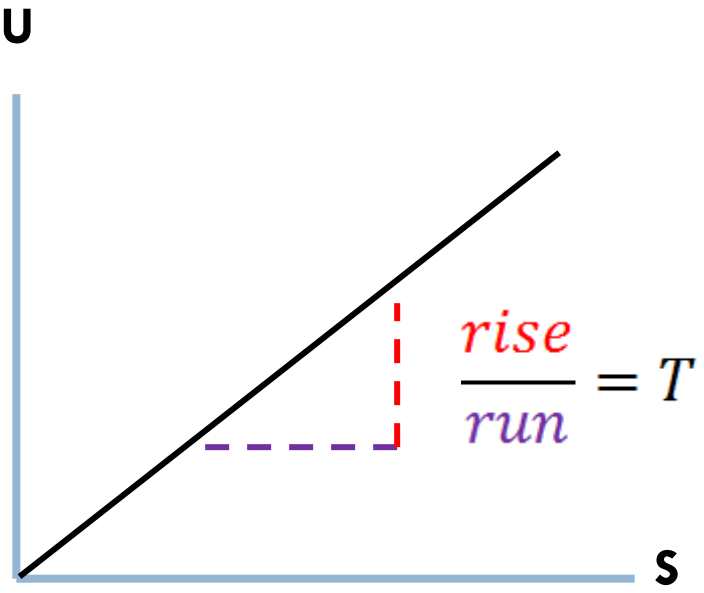
Entropy

$$S = k \ln \Omega$$

$$\Delta S \geq 0$$

What is Temperature Really?

$$T = \left(\frac{\partial U}{\partial S}\right)_{N,V}$$



Negative Absolute Temperature

- Absolute temperature is measured in Kelvin
  - Absolute Zero = 0 K = -273.15° C = -459.67° F
- Most of the world has positive temperature
  - Energy increases (+U)
  - Entropy increases (+S)
- Negative temperature is possible when
  - Energy increases (+U)
  - Entropy decreases (-S)

Hot, Hotter, Hottest

- "Hot" usually means higher temperature
- In general, something is "hotter" if heat flows out of it
- Heat flows to maximize entropy

https://www.target.com/p/green-bell-pepper-each/-/A-13728672

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https://www.publix.com/pd/red-chile-peppers/RIO-PCI-107070

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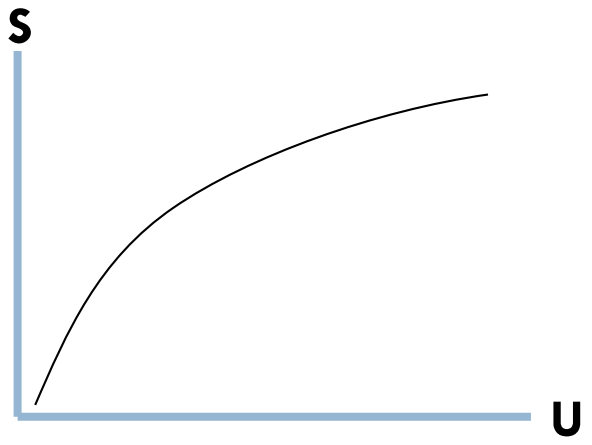
https://nypost.com/2015/08/04/eating-ghost-peppers-could-kill-you/

Negative Temperature Systems

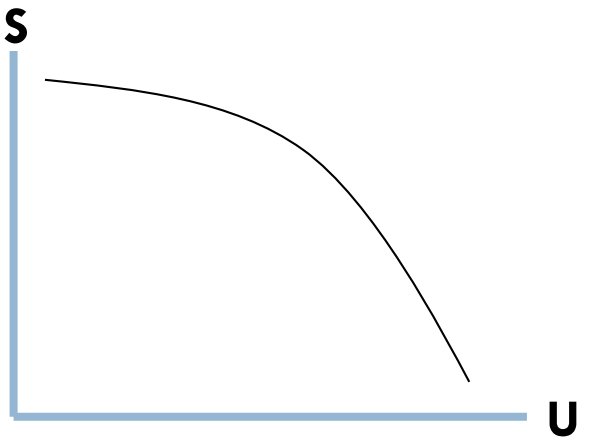
- There must be an upper energy bound
- Hotter than any positive temperature system

Positive vs. Negative

+ Temperature



- Temperature



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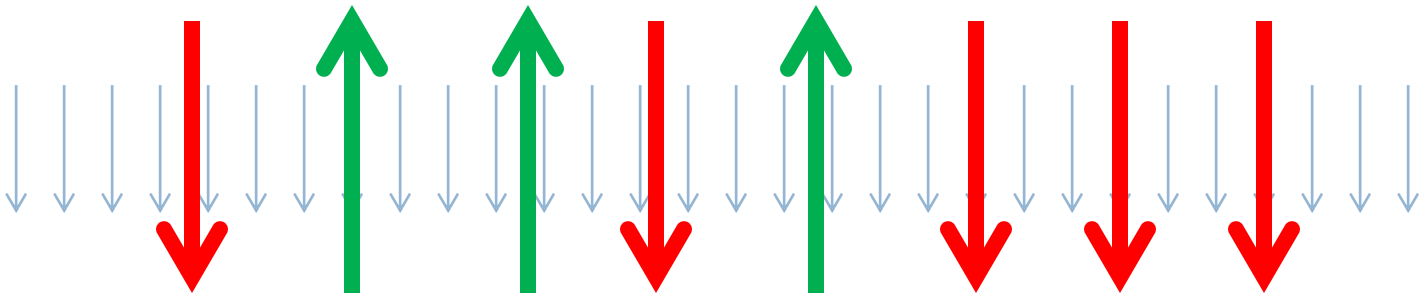
Two-State Paramagnet

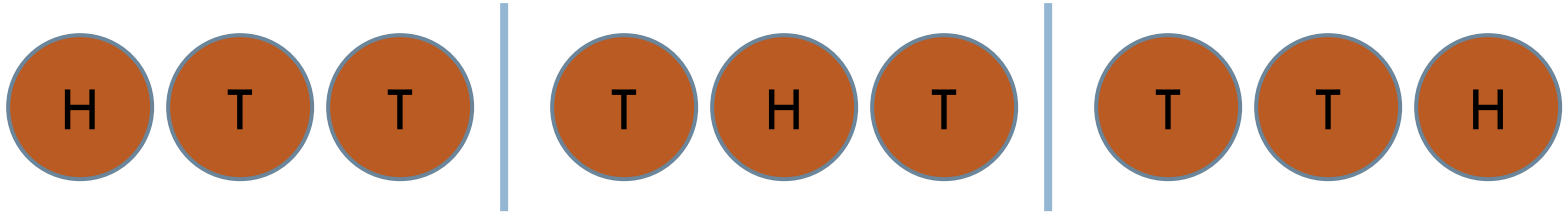
- Dipoles have two energy states: up and down
  - High energy when pointing up (μB)
  - Low energy when pointing down (-μB)

$$U_{tot} = \mu B(N_{\uparrow} - N_{\downarrow})$$



Multiplicity of Dipoles & Coins

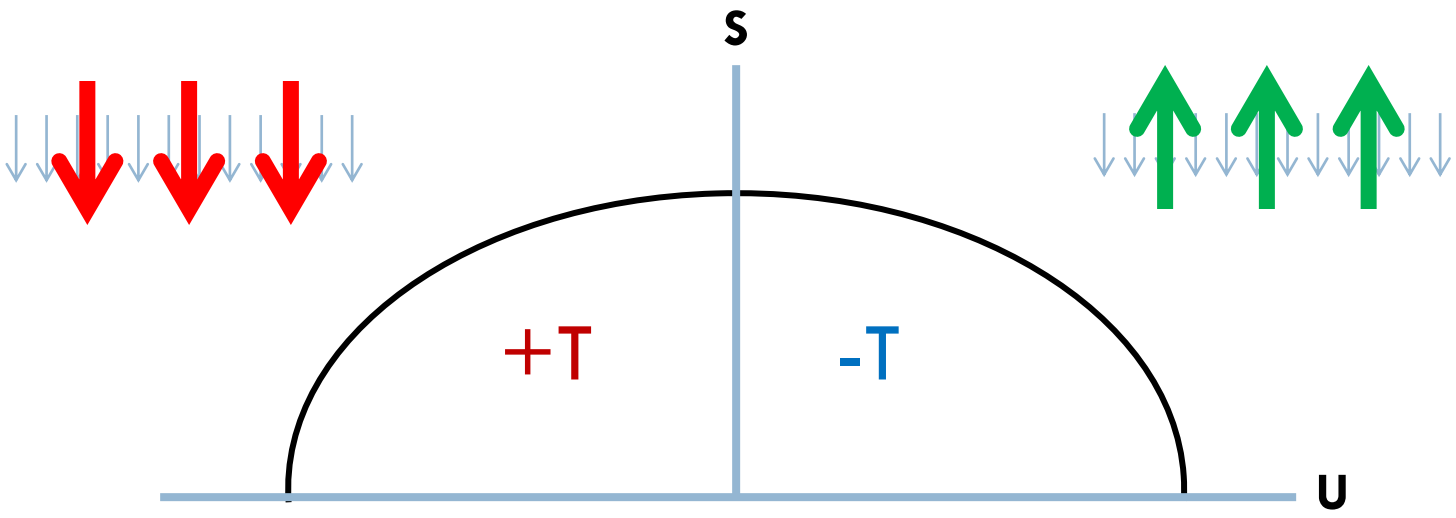
- We can imagine the dipoles as coins
- Suppose we flip 3 coins and get 1 heads and 2 tails. We have a multiplicity of 3.



$$\Omega = \binom{N}{N_\uparrow} = \frac{N!}{N_\uparrow!\, N_\downarrow!}$$

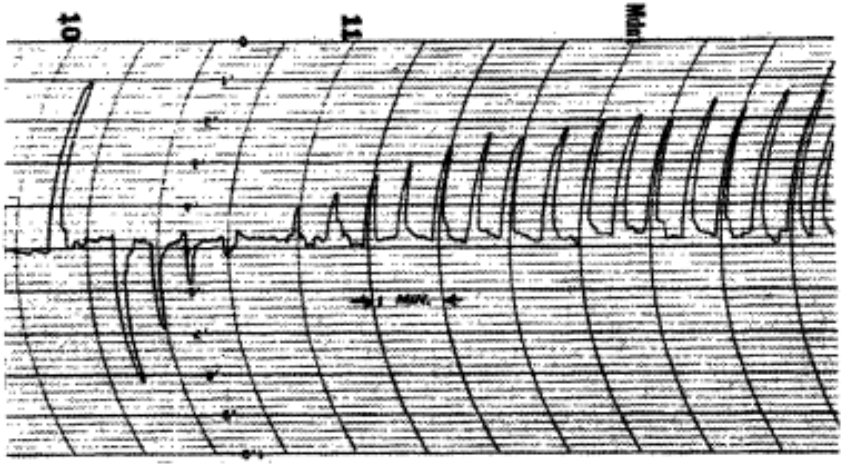
Energy Saturation

- First, adding energy increases entropy
- Eventually, though, entropy starts to decrease



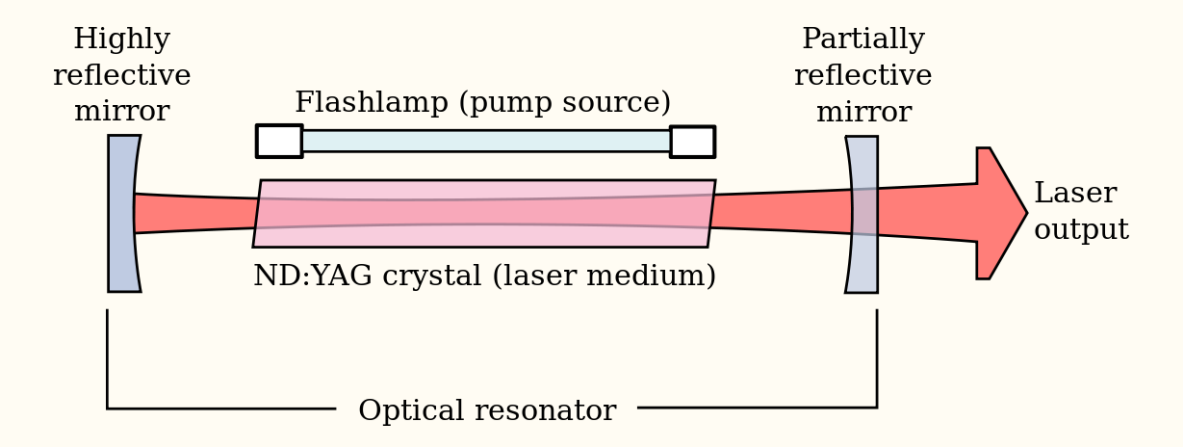
Purcell & Pound's Experiment

- Used lithium nuclei in a lithium-flouride crystal
- Crystal transferred between a 6376 gauss magnet and a -100 gauss solenoid
- Enough dipoles flipped to make their temperature negative



E. M. Purcell and R. V. Pound, Phys. Rev. **81**, 279 (1951)

Components of a Laser



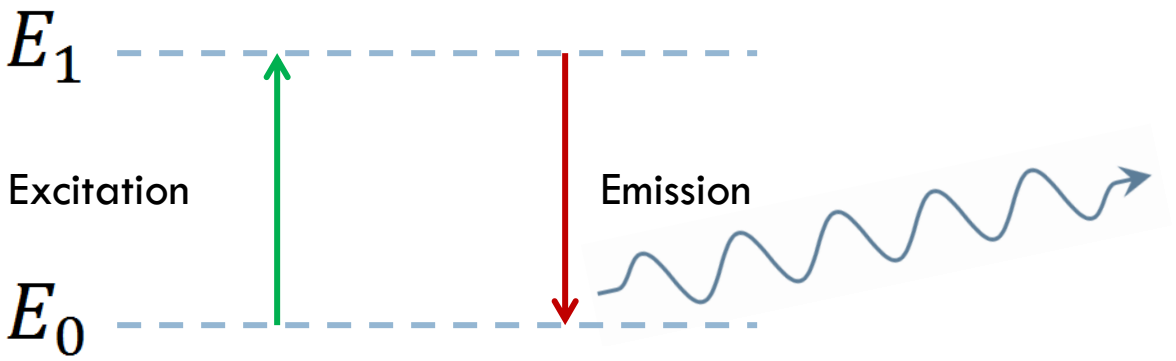
Lakkasuo, https://commons.wikimedia.org/wiki/File:Lasercons.svg

- Lasing medium
- Mirrors
- Flashlamp

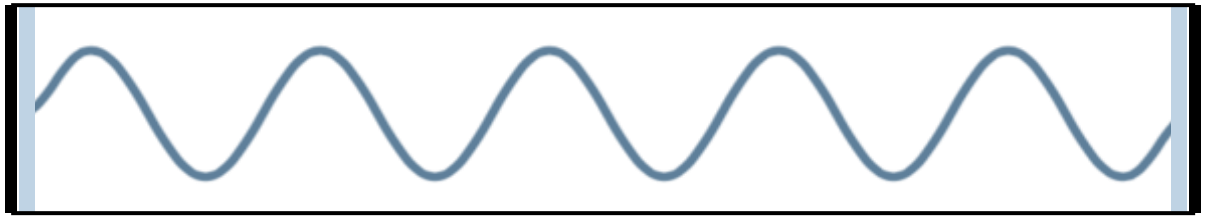
Marco Nero, http://www.laserfest.org/lasers/pictures.cfm

How a Laser Works

- A "lasing medium" has it's electrons excited



- Light is emitted to create standing waves



Population Inversion

Boltzmann Statistics: $P = \frac{1}{Z} e^{-\frac{E}{kT}}$

Equilibrium

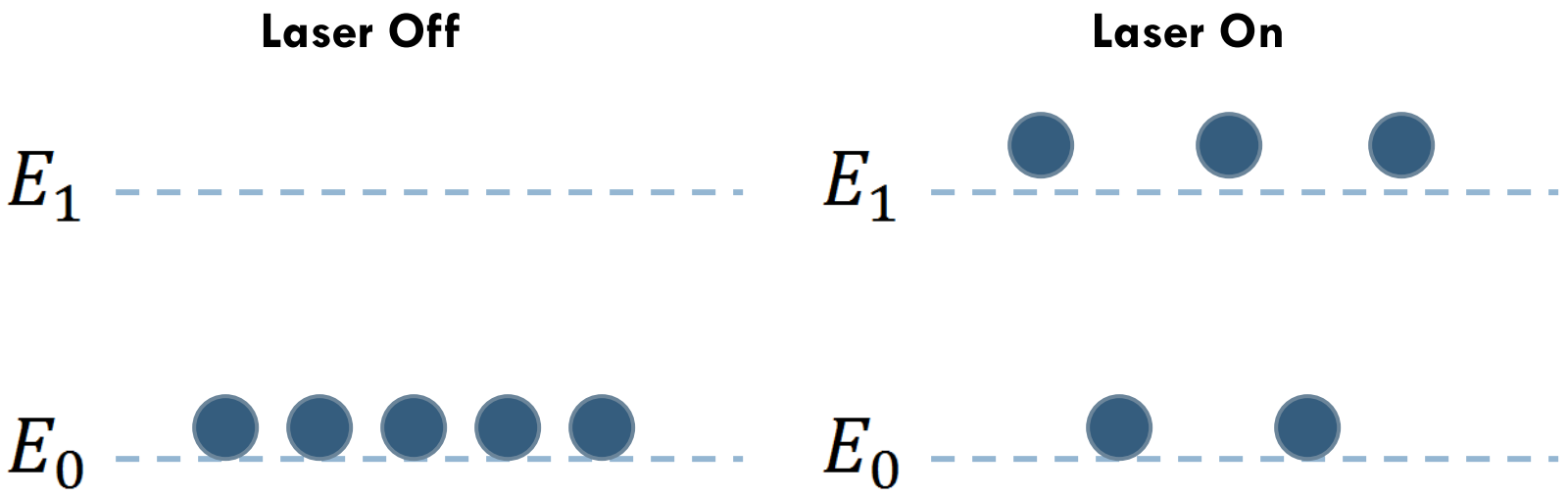
$$\frac{P_1}{P_0} = \frac{e^{-E_1/kT}}{e^{-E_0/kT}} < 1$$

Inversion

$$\frac{P_1}{P_0} = \frac{e^{-E_1/kT}}{e^{-E_0/kT}} > 1$$

Laser Inversion

- While off, most electrons are in ground states
- With "pumping" extra electrons are excited
- The electron population "inverts" and a negative temperature is reached



Review

1. Temperature, Entropy and Thermodynamics
2. Negative Absolute Temperature
3. System 1 : The Two-State Paramagnet
4. System 2 : Electron Gas in a Laser

Implications

Practical & Theoretical

- Negative temperatures are useful for modeling energy bounded systems
- Describes situations where entropy doesn't increase with internal energy

Hypothetical

- Dark energy displays parallels to negative temperature systems
- Negative temperature systems raise the possibility of a perfect efficiency heat engine

Acknowledgements